

Top Physics at the Tevatron



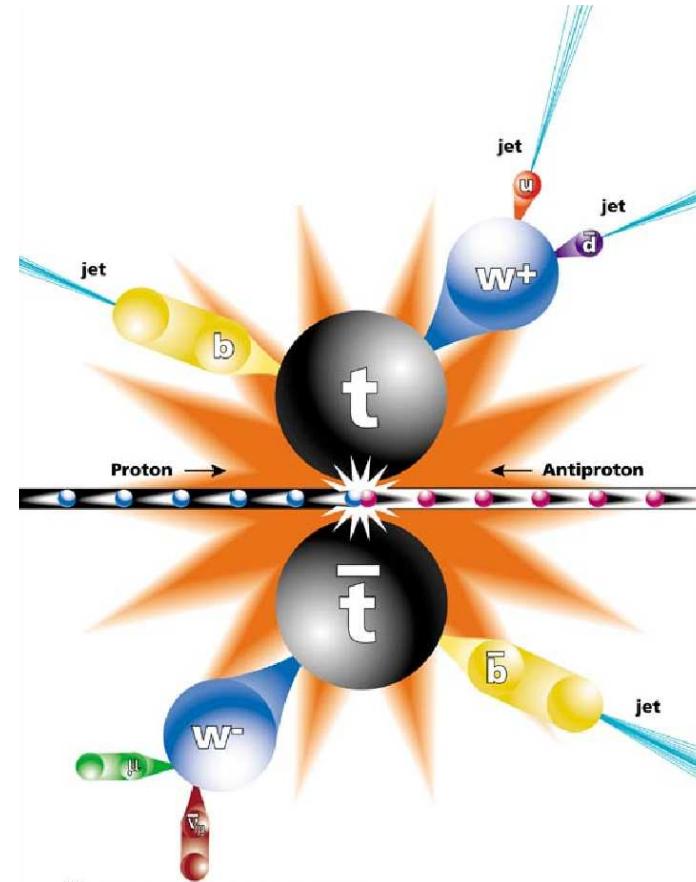
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Introduction

The Top Quark

- Discovered by CDF and DØ in 1995.
- Completes set of quarks in SM.
- Quantum numbers as for up-type quarks.
- Only its mass is a free parameter.
- Production and decay properties fully defined in Standard Model.



Only few of its predicted properties verified

Is the Top Quark special?

Yes, it is! It is ...

- more than 30 time heavier than the second heaviest elementary Fermion.
Its mass is surprisingly close to electro-weak scale.
- the only bare quark (i.e. decays before it hadronises)
- the last of the predicted quarks.

No, it isn't! It has ...

- the same electrical charge as u and c -quarks.
- the same weak couplings as the other quarks.
- the same colour charge as the other quarks.

Really??

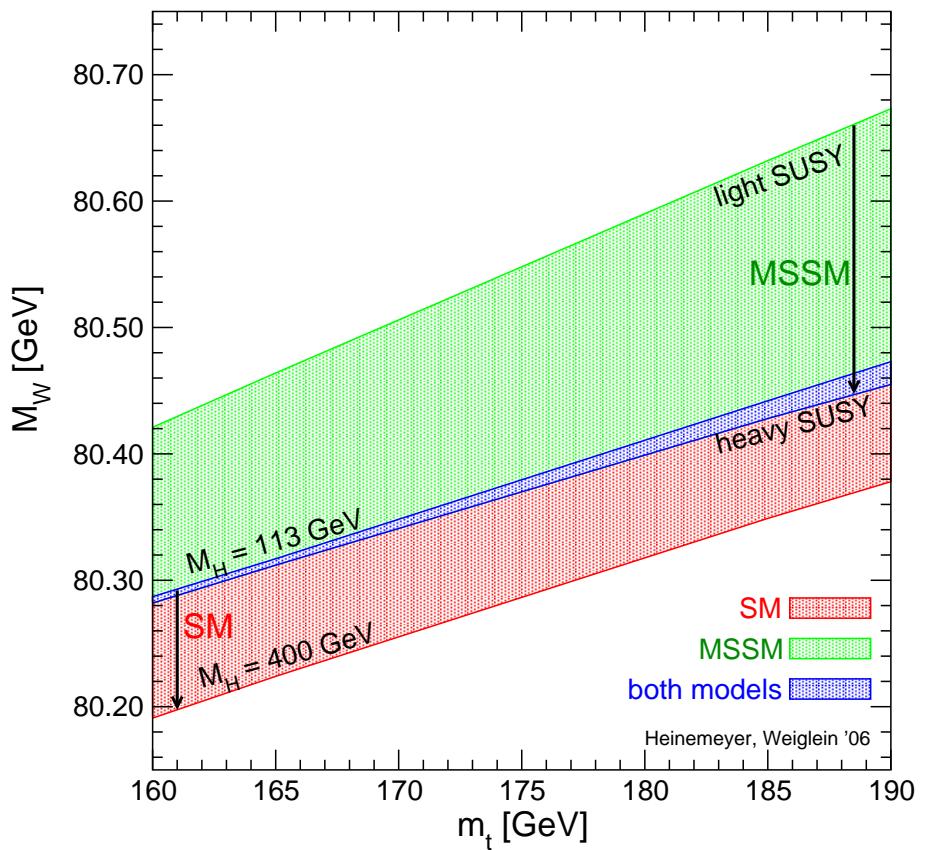
Maybe ...

- it has different couplings (\Rightarrow new physics)
- it isn't last quark (\Rightarrow new physics)

very interesting!

Relevance of the Top Mass

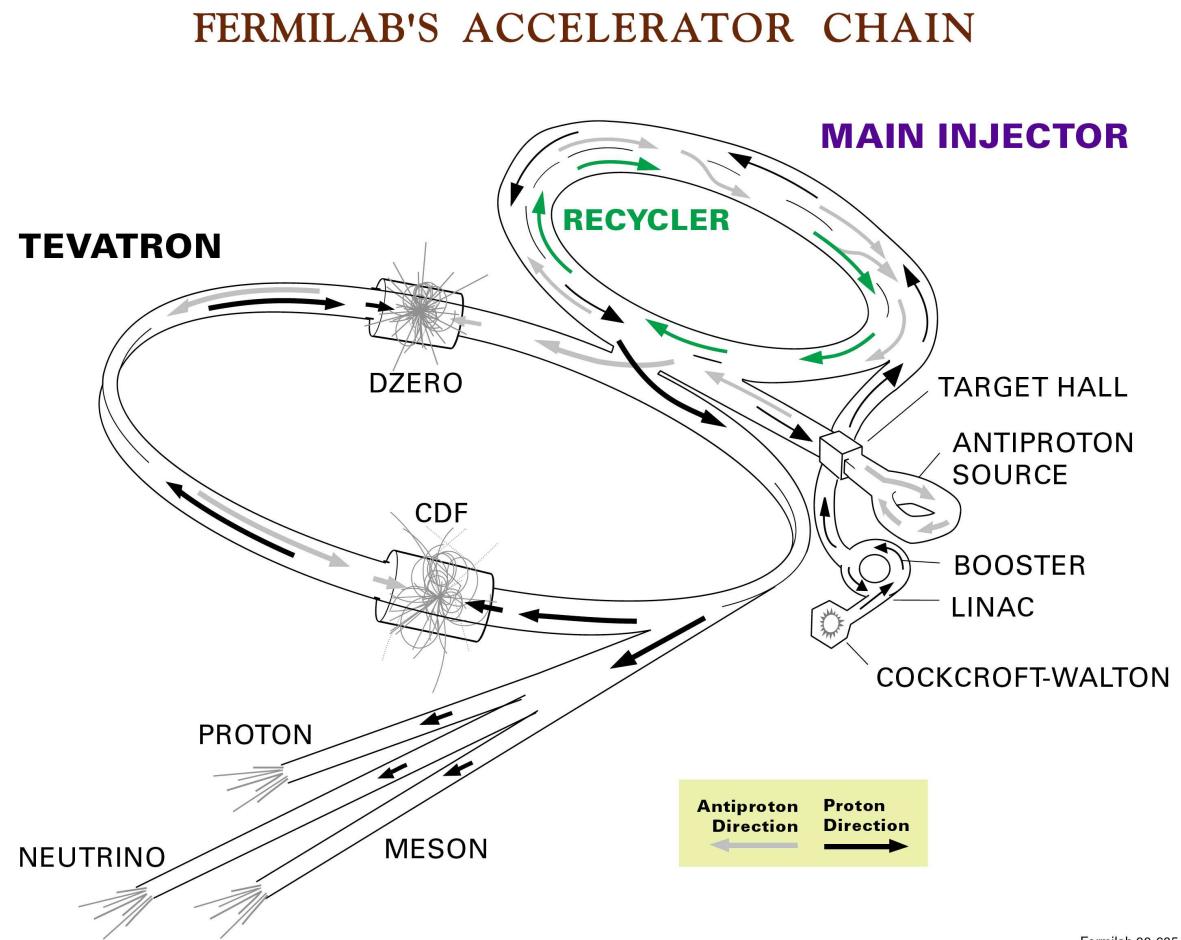
- Radiative corrections to electro-weak observables depend on the Top Mass.
- Allow prediction of the Higgs Mass
 - Differentiate between SM and extended Models.
- After Higgs discovery:
 - Consistency check of SM.



Experimental Environment

The $p\bar{p}$ Accelerator Tevatron

- Circumference 7 km.
- $p\bar{p}$ collisions
- Run I (1987-1995)
- Run II (since 2001)
Collision energy 2 TeV
- 2 experiments,
CDF and D \emptyset ,
record events.



The Tevatron



The (DØ) Detector

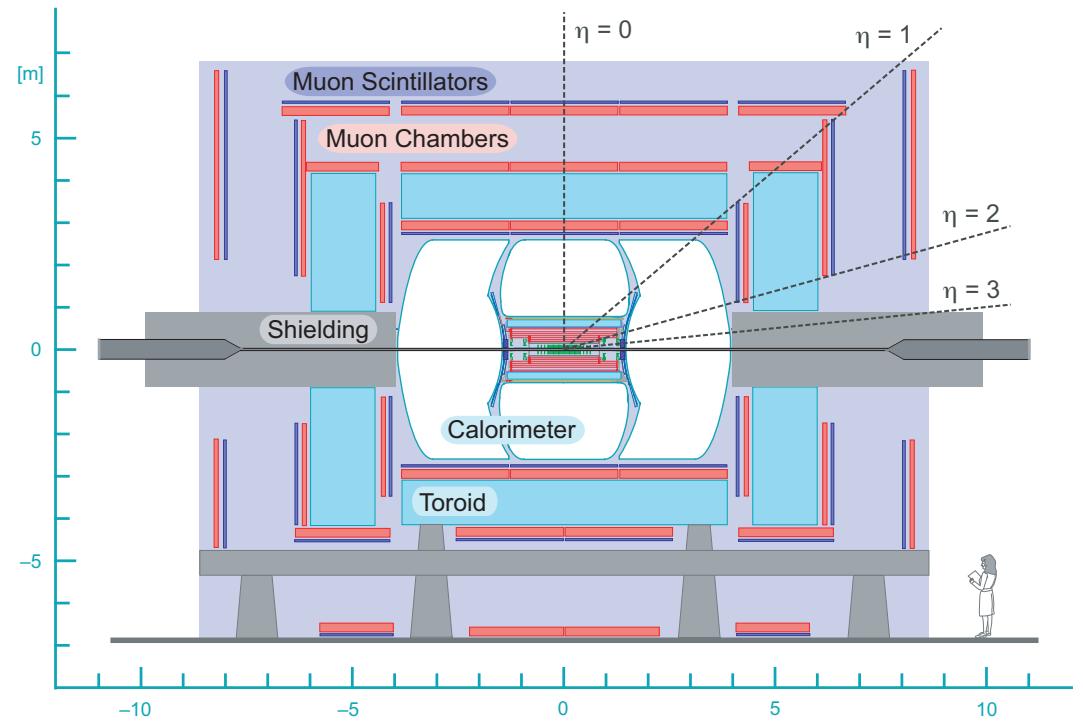
A 4π general purpose detector:

- Tracking in 2T solenoid
 - Silicon microstrip
 - Scintillating fiber tracker
- Calorimetry
 - Uranium/liquid argon
- Muon spectrometer
 - 3 layers of drift tubes
 - Toroidal magnetic field
(1.9T between inner 2 layers)

Dimensions: $12 \times 12 \times 20 \text{m}^3$

Note: Polarangle θ against beam axis

$$\text{Pseudorapidity } \eta = -\ln \tan \theta/2$$



Reconstructed Physics Objects

Muon

Track in Muon chambers (outside the calorimeters)

Electron

Energy deposition only in the innermost ('em') calorimeter part.

Jets (sign of quarks or gluons)

Accumulations of energy deposited in the 'hadron' calorimeters.
CDF and DØ usually use Cone jet algorithms.

Missing Transvers Energy, \cancel{E}_T (sign of neutrinos)

Negative sum of all energy measured transverse to beam directions

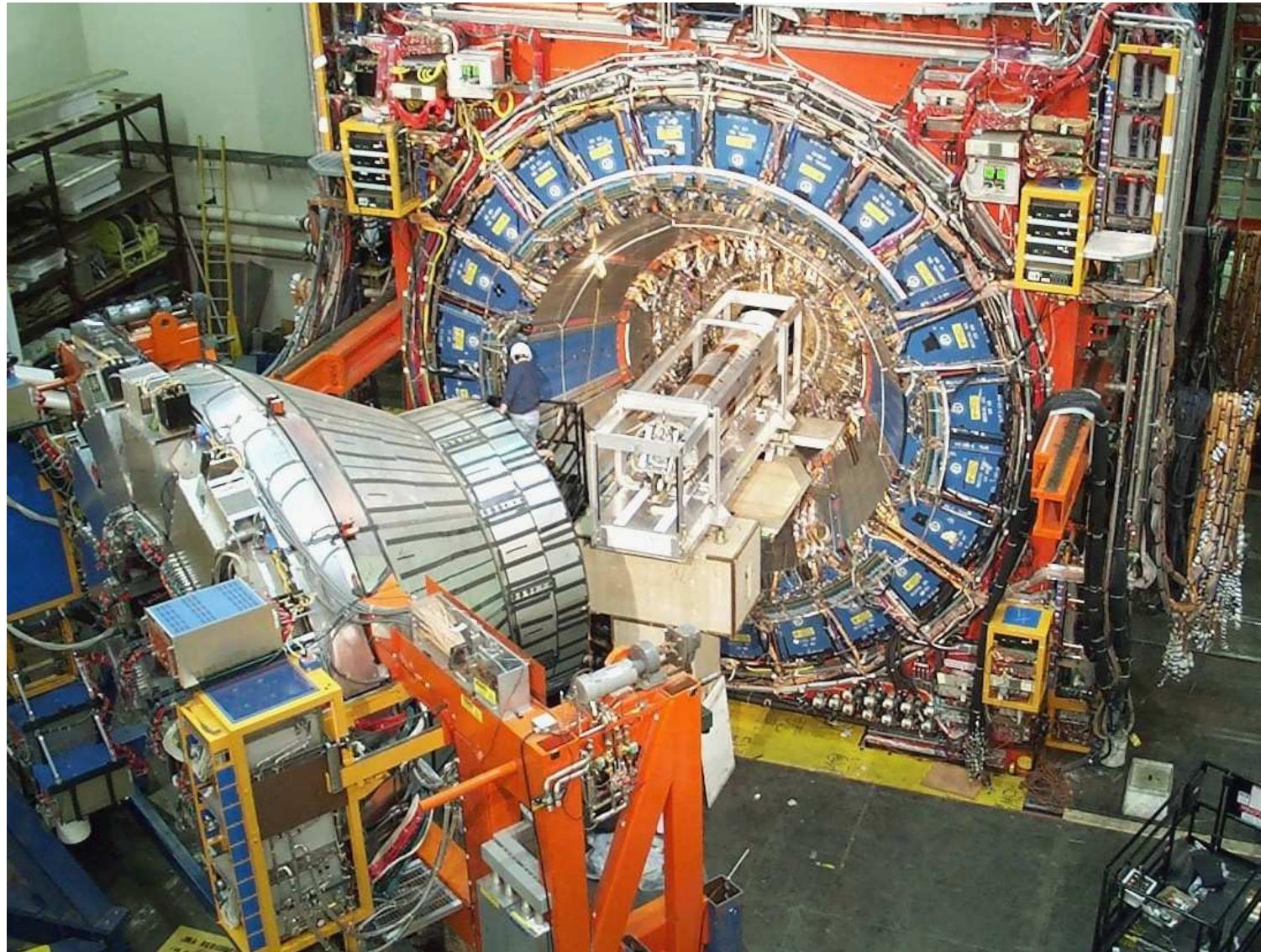
B-Tag (sign of *b*-quarks)

Long lifetime of *B*-Hadrons lead to secondary vertices, detected with tracking.

- International collaboration
- 90 institutes, ~ 700 physicists
- 18 countries from 4 continents

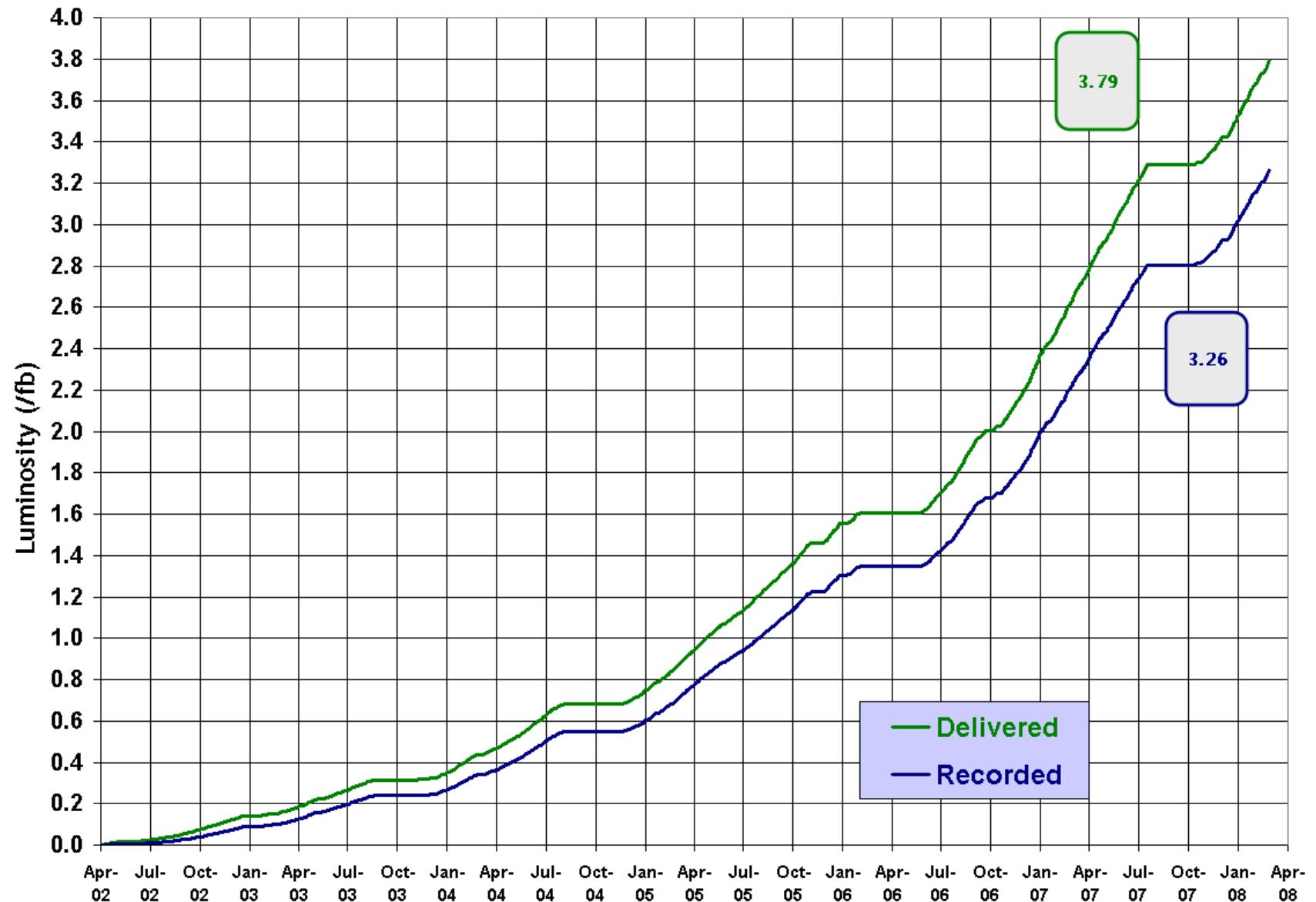


CDF



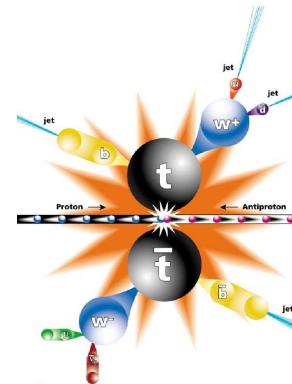
DØ RunII Integrated Luminosity

Apr 2002 – March 2008



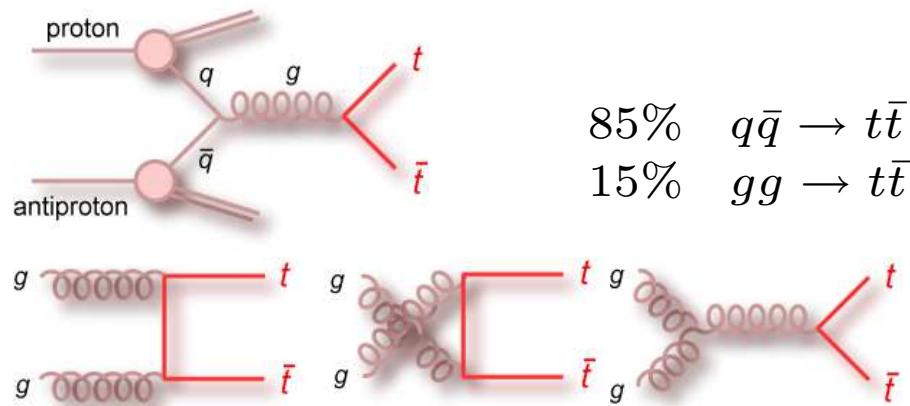
Outline

- SM Top Physics
- Top Quark Mass
- Top Production
- Top Decay
- Summary



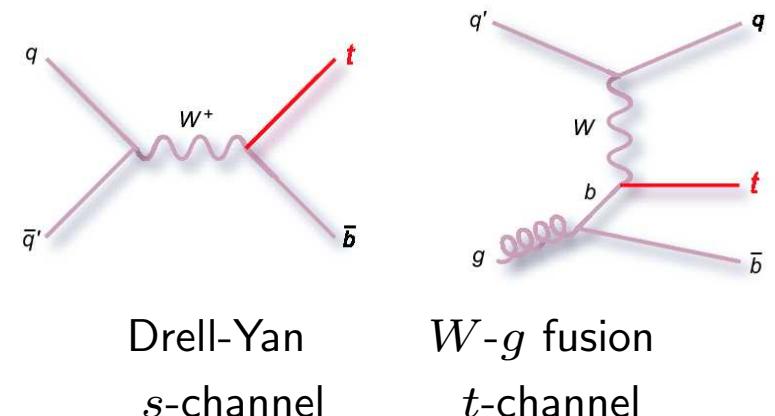
Top Quark Production at the Tevatron

Strong top production



- $\sigma(t\bar{t}) = 6.77 \pm 0.42 \text{ pb}$

Weak top production



- $\sigma(t) = 2.9 \pm 0.3 \text{ pb}$

Per integrated luminosity of $\sim 1 \text{ fb}^{-1}$
around 7000 top pairs and 3000 single tops expected.

Top Quark Decay

Top quarks decay to bW (nearly) 100%.

Pair Production Signatures

Decay modes are defined by W -decays:

- Dilepton $(2b + 2l + 2\nu)$
- Lepton+jets $(2b + 2q + l\nu)$
- Alljets $(2b + 4q)$

Top Pair Decay Channels

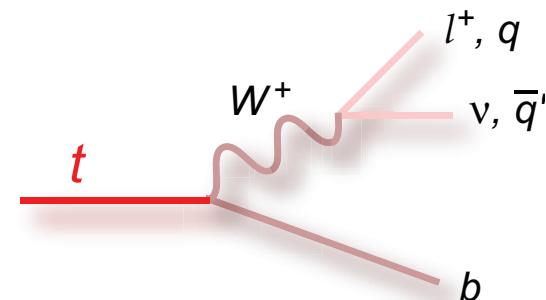
$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
$e^- \tau$	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
$e^- \mu$	$e\mu$	$\mu\tau$	$\mu\tau$	muon+jets	
e^-	$e\tau$	$e\tau$	$e\tau$	electron+jets	
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$

Single Top Signatures

Defined by W -decays and channel;

e.g. leptonic decay:

- s-channel $(2b + l + \nu)$
- t-channel $(b + j + l + \nu)$



Measurement of the Top Mass

Template Method (CDF)

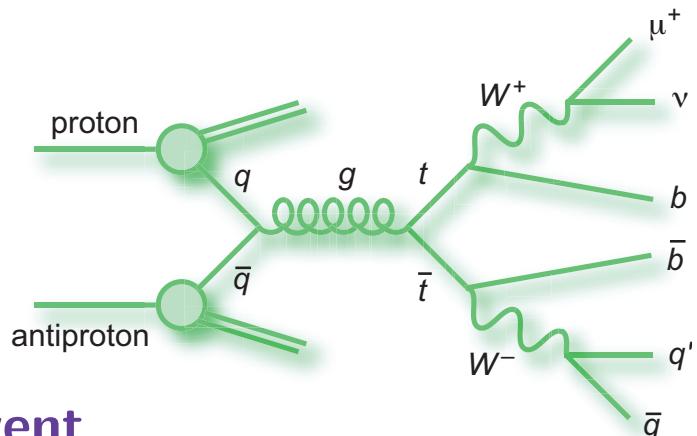
- Combination of $l+jets$ and Dilepton
- Explanation concentrates on $l+jets$

Determination of the top mass for each event

Reconstruct four-momenta of t -Quarks in each individual event:

- Reconstruction of ν momentum
- (Correct) association of $l\nu$ and 4 jets to 2 top-quarks
- Sum of associated four-momenta is $m^2 = E^2 - \vec{p}^2$

In reality done with fit: Same top-mass and nominal m_W as constraints.
Precise energy measurement & correct association crucial:
 $\min. \chi^2$ solution used.



Template Method (CDF) II

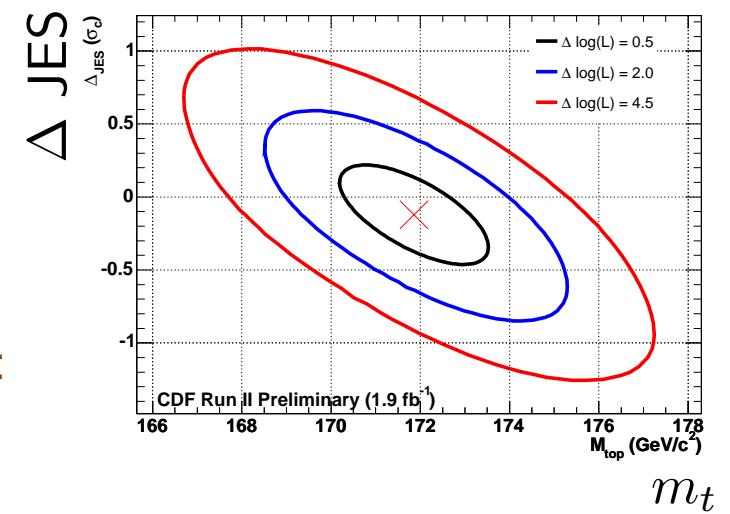
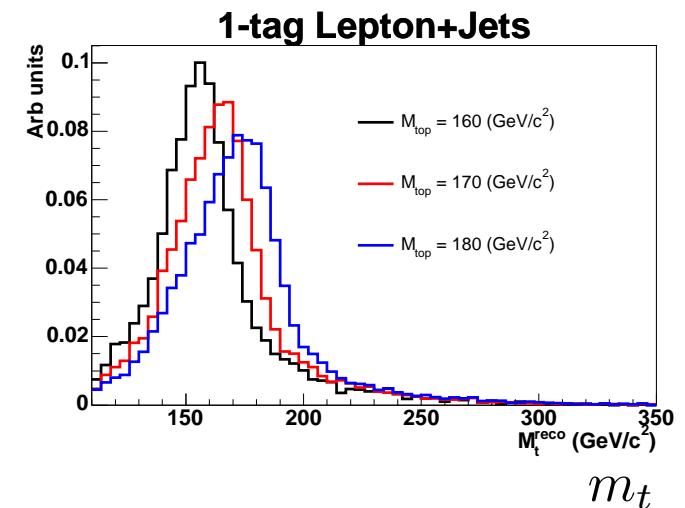
- Compare reconstructed Mass & further Obs. with simulation (templates)
 - for various m_t
 - including expected Background.
- Find m_t with best agreement.

Restriction of energy scale

- Templates for m_W reconstructed from m_{jj} with various energy scales (JES).
- Self calibration of the energy scale.

Top mass and JES from 2d-fit to MC (1.9 fb^{-1}):

$$m_t = 171.9 \pm 1.7(\text{stat + JES}) \pm 1.0(\text{syst}) \text{ GeV}$$



Matrix Element Method (DØ)

Determine top mass from likelihood

Likelihood for observed kinematic configuration x as function of m_t und JES:

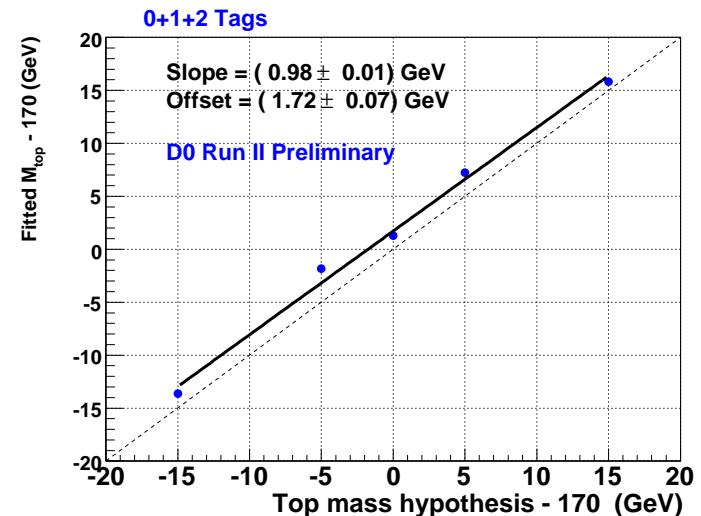
$$P_{\text{evt}}(x; m_t) = f_{\text{top}} P_{\text{sgn}}(x; m_t) + (1 - f_{\text{top}}) P_{\text{bkg}}(x)$$

$$P_{\text{sgn}}(x; m_t) = \frac{1}{\sigma_{t\bar{t}}(m_t)} \int dq_1 dq_2 \underbrace{d^n\sigma(q\bar{q} \rightarrow t\bar{t} \rightarrow y; m_t)}_{\text{Matrix Element}} \underbrace{f(q_1)f(q_2)}_{\text{PDFs}} \underbrace{W(y, x; \text{JES})}_{\text{Resolution}}$$

- Maximise likelihood of sample to find m_t and energy scale (JES).
- Calibration by comparing to MC

Top mass after calibration (2.1 fb^{-1}):

$$m_t = 172.2 \pm 1.1(\text{stat + JES}) \pm 1.6(\text{syst}) \text{ GeV}$$



Combination of direct top mass results

Combination of RunI and RunII results of both experiments:
Best Linear Unbiased Estimator (BLUE), i.e. including correlations.

Systematic uncertainties

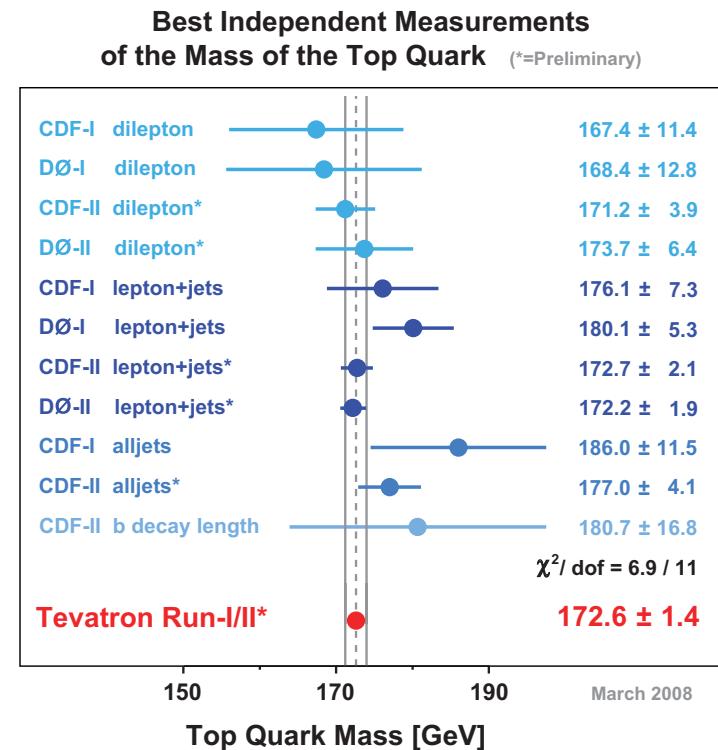
- Jet energy scale (light Quarks)
still dominating
- Jet energy scale in b -jets
- Signal, Background, . . .

World average (3.2008)

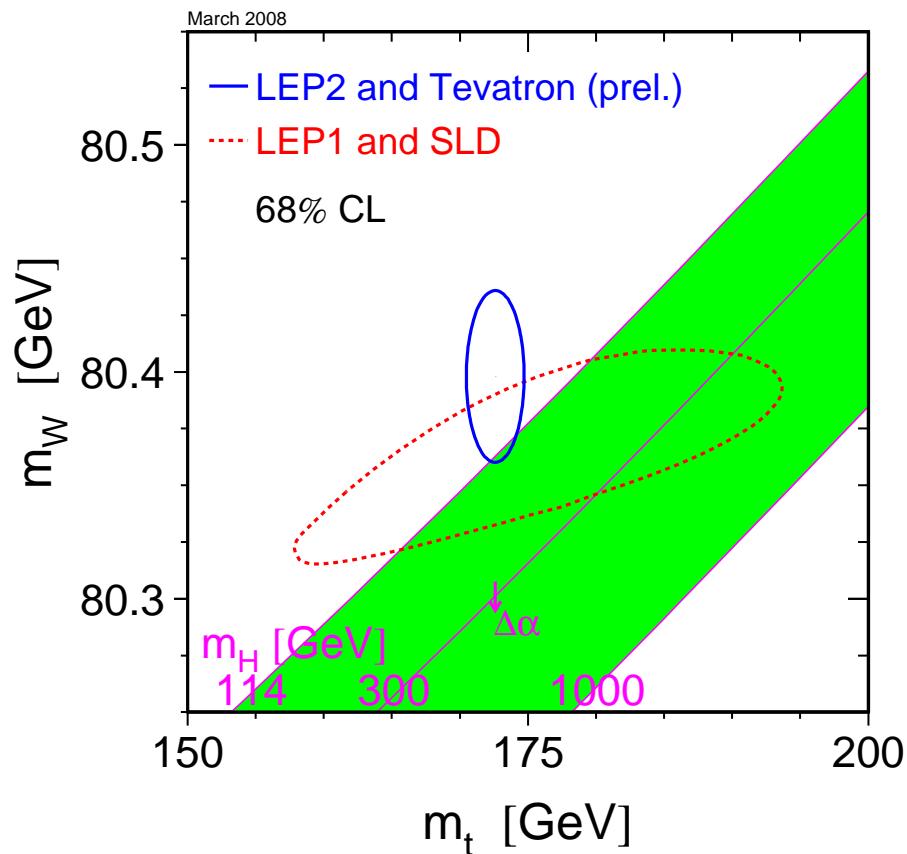
$$172.6 \pm 0.8(\text{stat}) \pm 1.1(\text{syst}) \text{ GeV}$$

Total uncertainty: 1.4 GeV

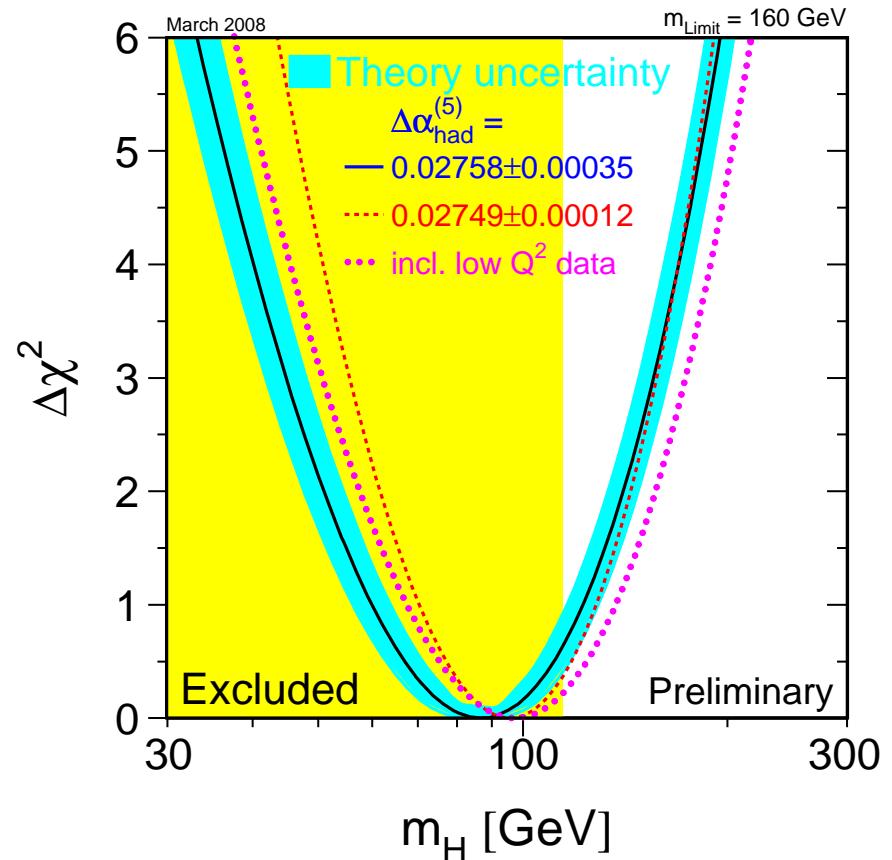
Dilepton	$169.3 \pm 3.1 \text{ GeV}$
$l+jets$	$172.4 \pm 1.5 \text{ GeV}$
Alljets	$177.3 \pm 3.9 \text{ GeV}$



Top Mass in electroweak fits



Combined m_W and m_t results
barely touches SM-region



Higgs mass projection
 $M_H \leq 190 \text{ GeV} (95\% \text{CL})$
(incl. lower limit)

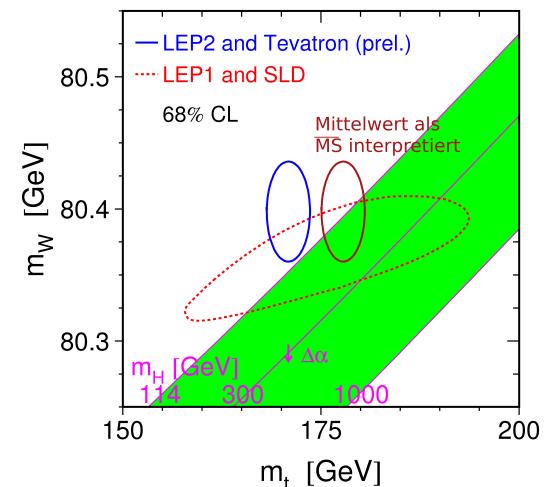
Open issues in top mass measurements

Do we understand what is measured?

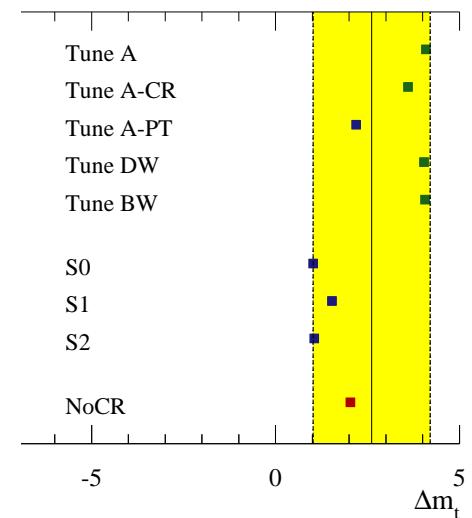
Pole mass, $\overline{\text{MS}}$ -mass, ...?

- Measurements fit or calibrate to MC
- So we measure the Pythia parameter PARP(6,1)
- Current interpretation: it is the pole mass.
- Uncertainties arise from soft gluon radiation
- How precise is the assumption? 1, 2, 5 GeV??

Alternative methods for mass determination important.



Skands, DW, EPJ C52 (2007)



Strong production, top pairs

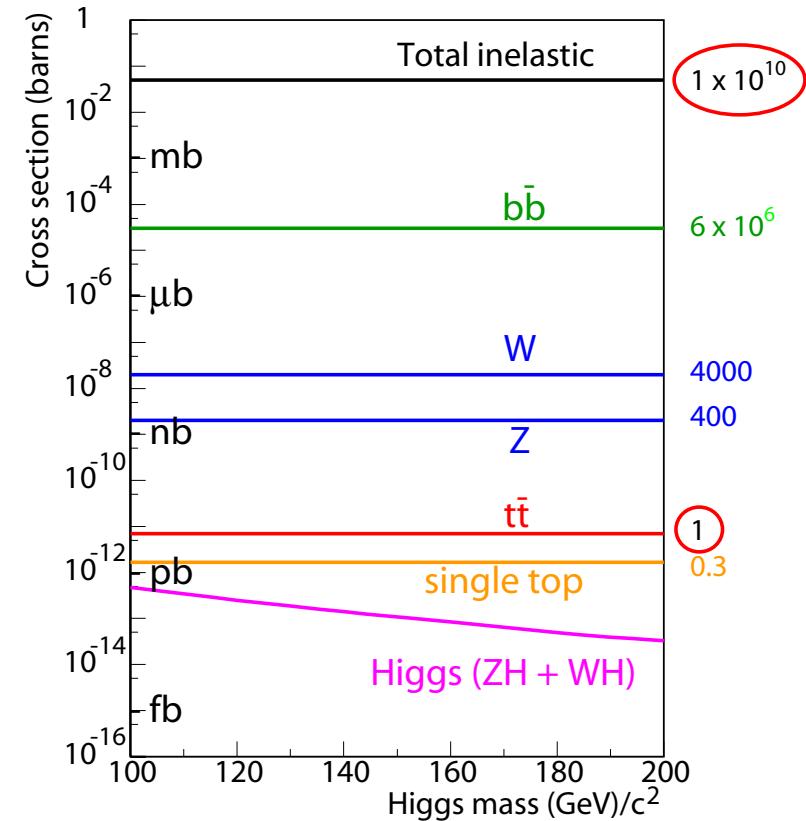
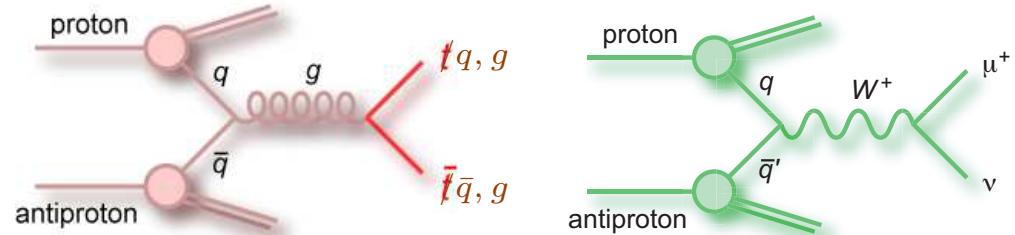
$$\sigma_{t\bar{t}} = \frac{N - B}{\varepsilon \mathcal{L} \cdot \text{BR}}$$

Dominant backgrounds

- Multijet events
($q\bar{q}$ or gg + gluon radiation)
- W +jets
- Z +jets

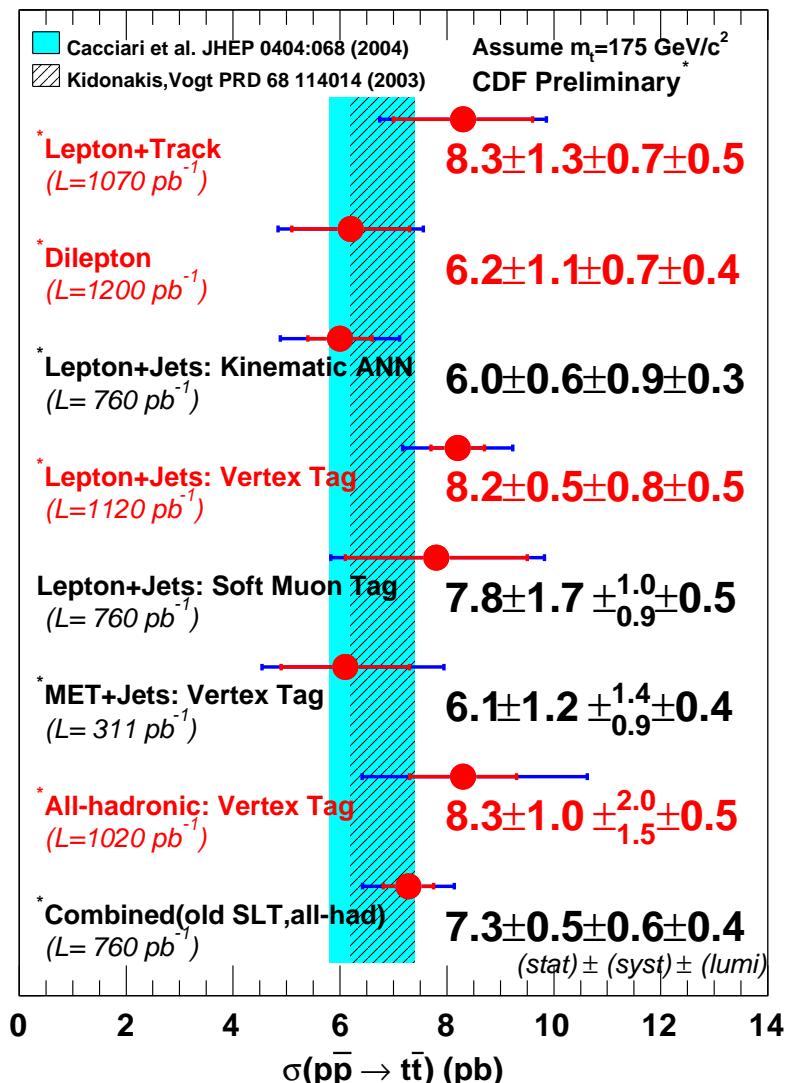
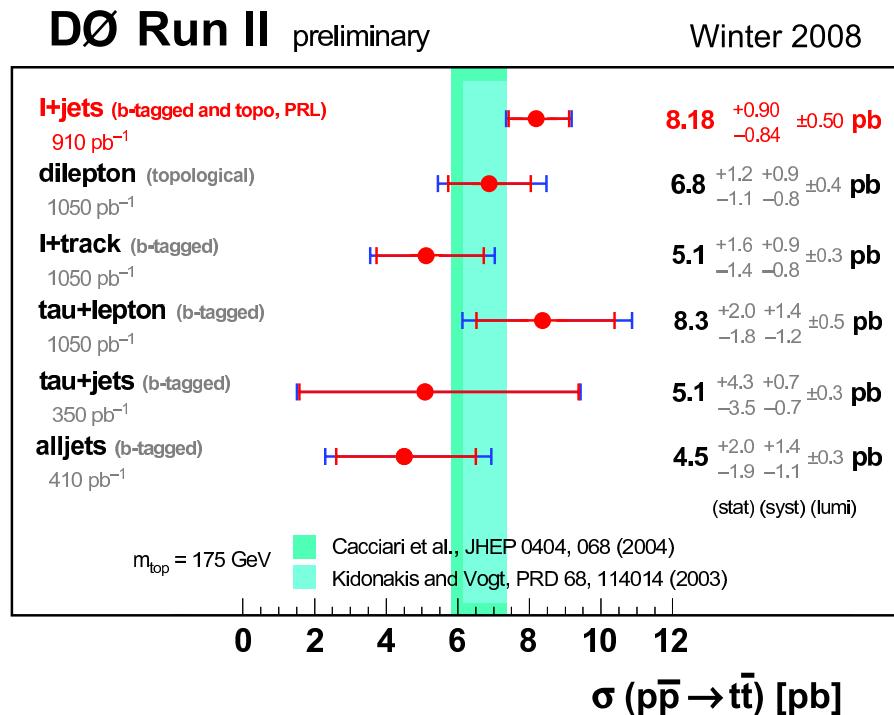
Simulation of multijet events
difficult and unprecise

Background estimation from data!



Results on $t\bar{t}$ cross-section

- Various channels & methods
 - Good agreement among each other and with theory: $\sigma_{t\bar{t}} = 6.77 \pm 0.42 \text{ pb}$
for $m_t = 175 \text{ GeV}$



Top mass from cross-section

$\sigma_{t\bar{t}}$ depends on the top mass.

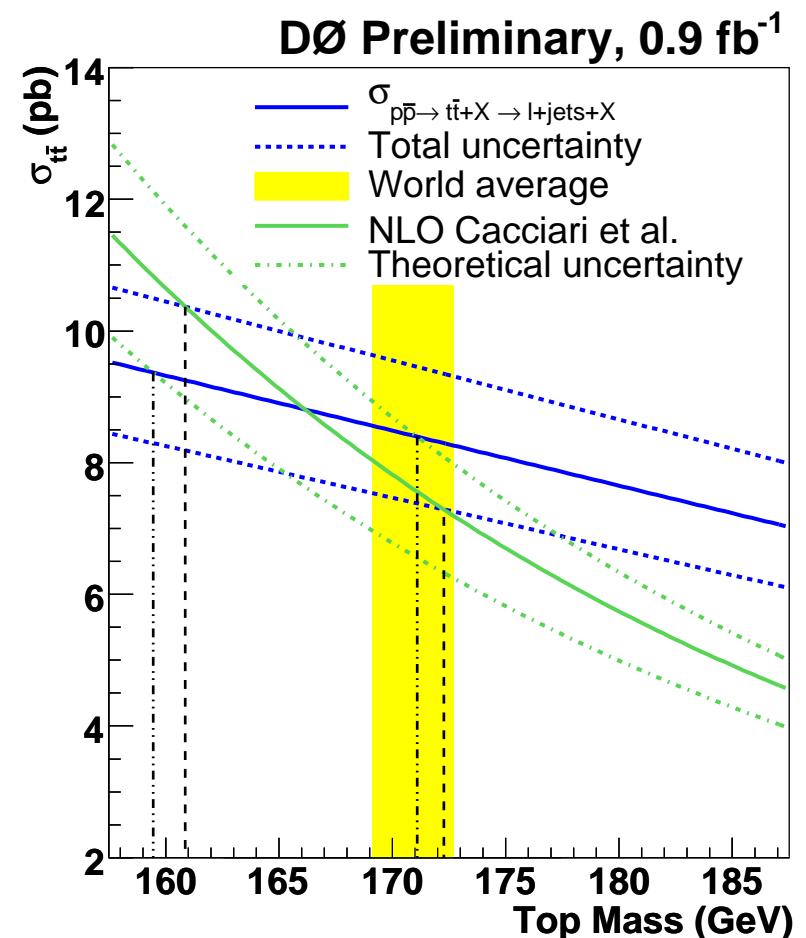
Both the theoretical prediction
and the experimental measurements.

DØ (z.B.: Cacciari et al.)

$l+jets:$ $m_t = 166.1^{+6.1}_{-5.3}(\text{exp})^{+4.9}_{-6.7}(\text{theo}) \text{ GeV}$

Dilepton $m_t = 174.1^{+9.8}_{-8.4}(\text{exp})^{+4.2}_{-6.0}(\text{theo}) \text{ GeV}$

Here m_t is the pole mass!

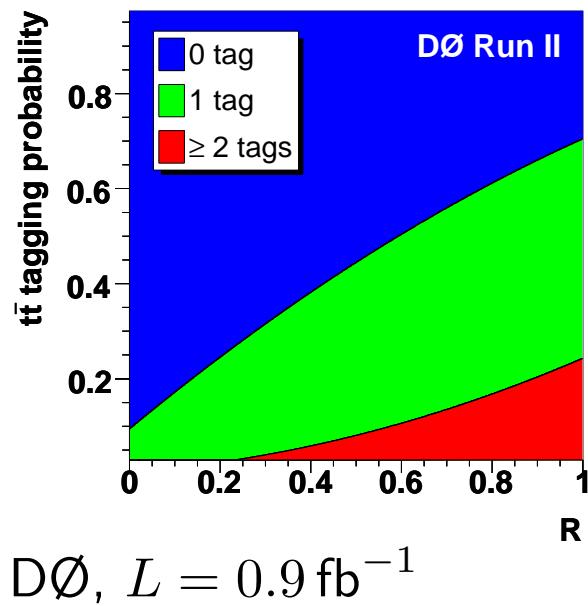


Consistent with direct results; larger uncertainties

Branching ratio (and cross-section)

From number of events with 0,1,2 identified b -jets, simultaneously

$$R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = 0.97 \pm 0.09$$
$$\sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84(\text{stat+syst})} \pm 0.50_{(\text{lumi})} \text{ pb}$$



Limits for the CKM matrix

Assuming 3 generations:

$$\sqrt{R} = |V_{tb}| > 0.88 \text{ at 95% C.L. (SM: 0.9991)}$$

Current best experimental Limit

For arbitrary number of generations:

$$\frac{|V_{tb}|^2}{|V_{ts}|^2 + |V_{td}|^2} > 3.76 \text{ at 95% C.L.}$$

No deviation from SM

Resonante Top Paarproduktion

No resonant top production in SM

Some models contain heavy resonances with decay to $t\bar{t}$

Visible in invariant mass $\frac{d\sigma}{dm_{t\bar{t}}}$

Search for narrow resonances

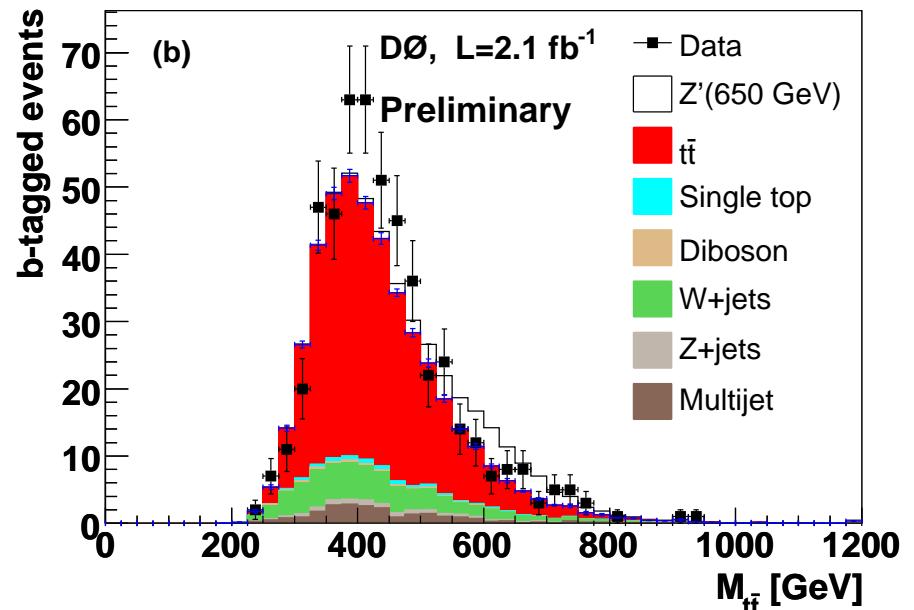
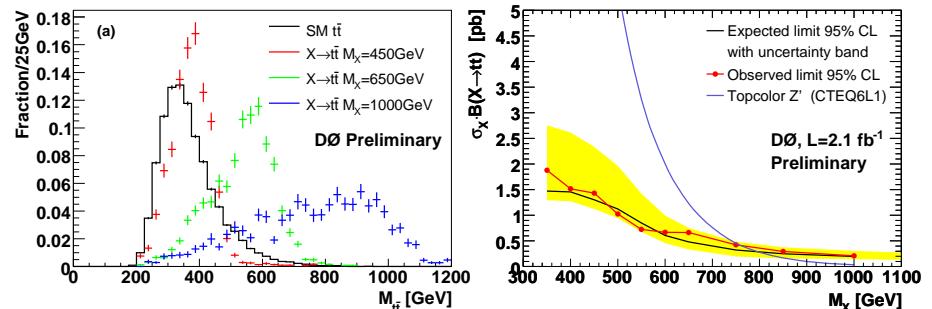
No significant deviations.

E.g. topcolor-assisted technicolor:

CDF: $M_{Z'} > 720 \text{ GeV}$ (expected 710 GeV)

DØ: $M_{Z'} > 760 \text{ GeV}$ (expected 795 GeV)

(CDF: $L = 0.9 \text{ fb}^{-1}$; DØ: $L = 2.1 \text{ fb}^{-1}$)

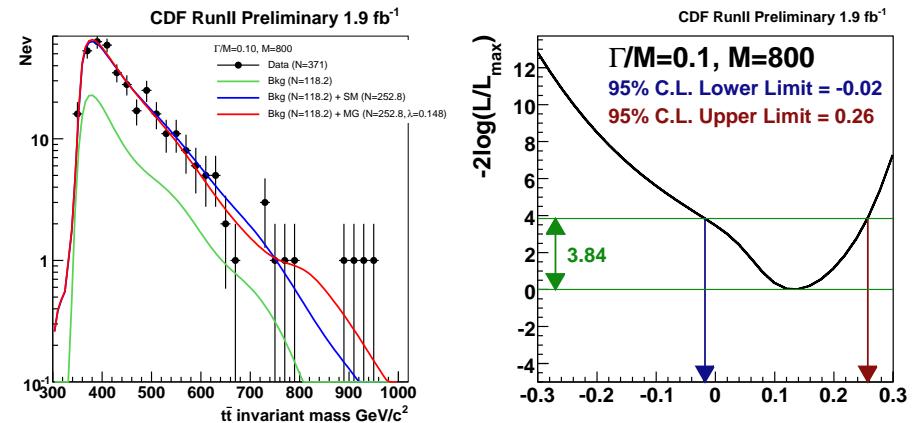


Resonant production through massive gluon

CDF: 1.9 fb^{-1}

For various hyp. gluon masses

Determine coupling as fraction of the strong coupling

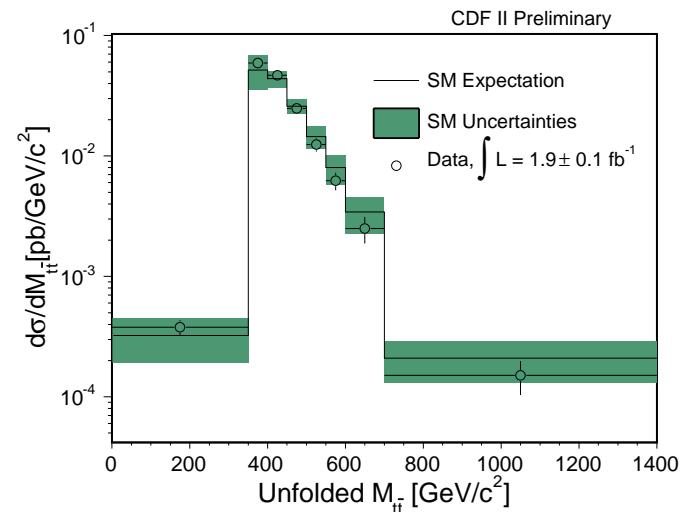


Differential cross-section

CDF: 1.9 fb^{-1}

Unfolding allows to determine differential cross-section

Agreement with SM: 45%



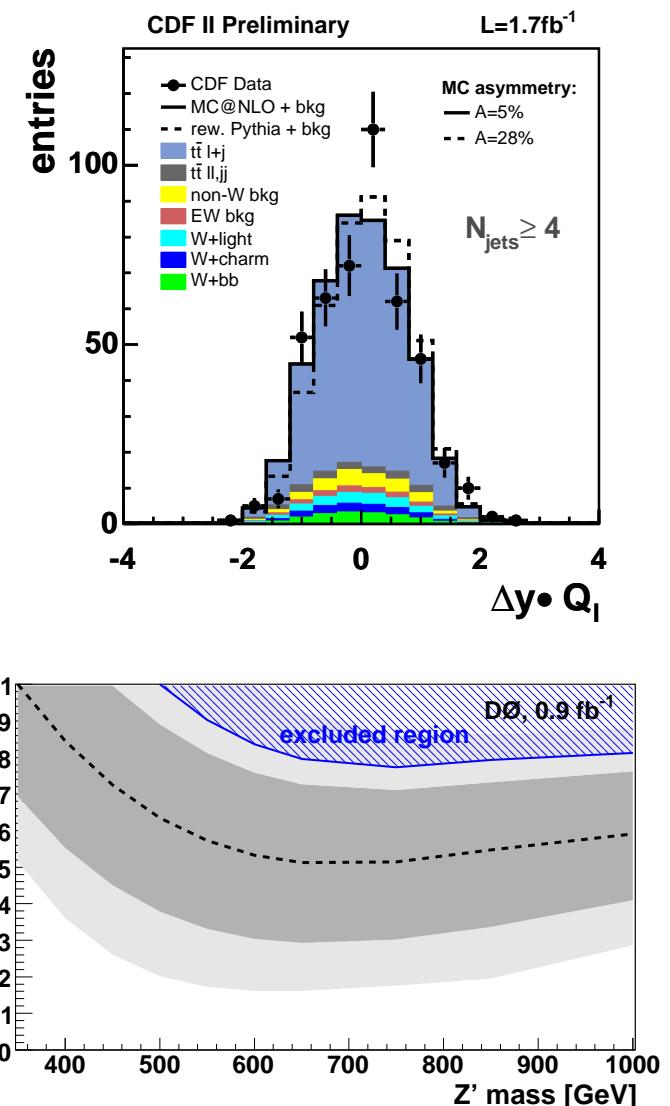
Forward Backward Asymmetry

- Initial state is not charge symmetric
- No need for final state to be
- Despite no single graph is asymmetric
SM: asymmetry from interference at NLO

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B} = 0.12 \pm 0.08_{\text{stat}} \pm 0.01_{\text{syst}}$$

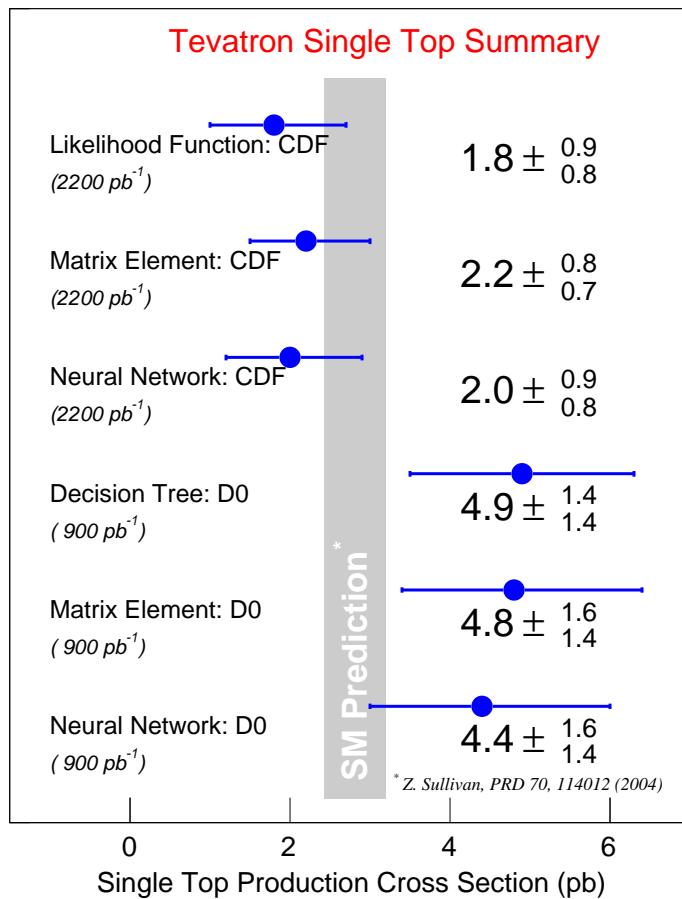
with F : $y_t > y_{\bar{t}}$ and B : $y_t < y_{\bar{t}}$.

- Data consistent with SM:
Allows limit wide resonance prod

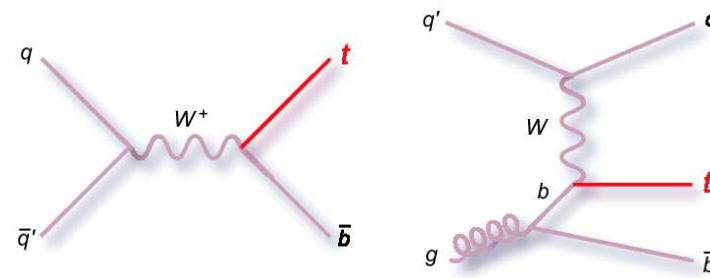


Electroweak production, Single Top

Cross-section



SM prediction: $\sigma_{s+t} = 2.9 \text{ pb}$



Experimentally very challenging
Huge Background from $W + \text{jets}$
3 multivariate analyses per Exp.

Significance

Excess over 0-t-Hypothesis

DØ 3.6σ (0.9 fb^{-1})

CDF $3 - 3.5\sigma$ (1.5 fb^{-1})

Evidence for single top in both experiments

Interpretation as V_{tb}

Assuming SM couplings V_{tb} can be derived:

CDF: $|V_{tb}| = 0.88^{+0.14}_{-0.12} \pm 0.07$

DØ: $|V_{tb}| = 1.3 \pm 0.2$

Reduction to physical range yields

CDF: $|V_{tb}| > 0.59$

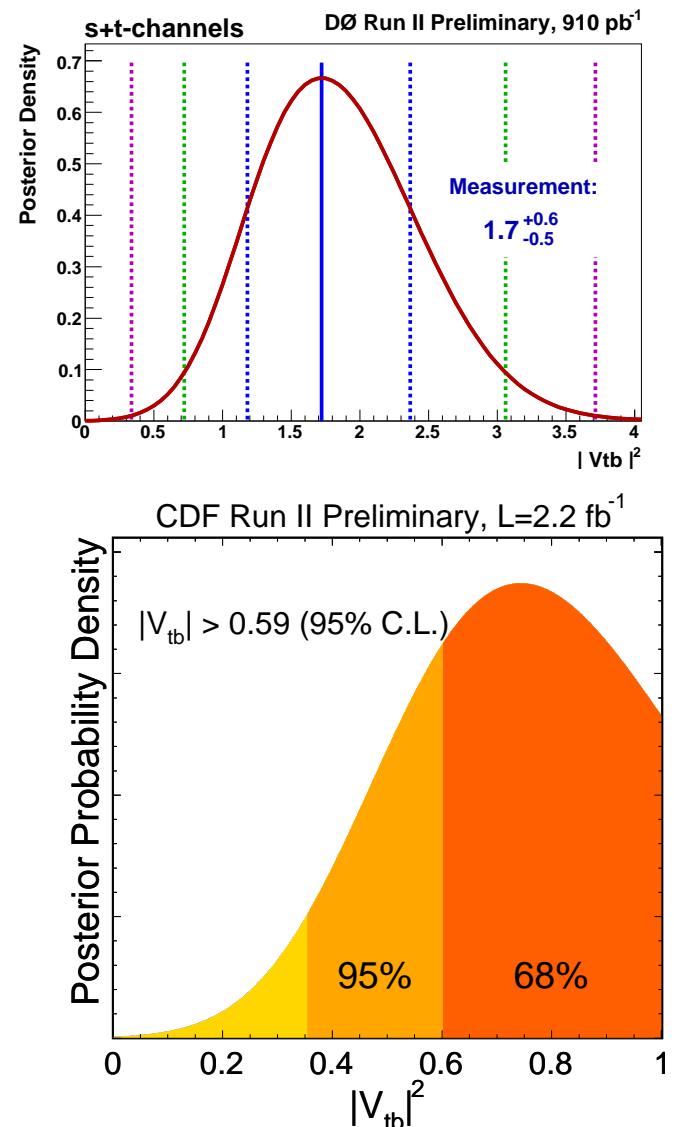
DØ: $|V_{tb}| > 0.68$

with no assumption on the number of generations

Reminder:

top pair production *for three generations*

$|V_{tb}| > 0.88$



Anomalous Single Top Production at HERA

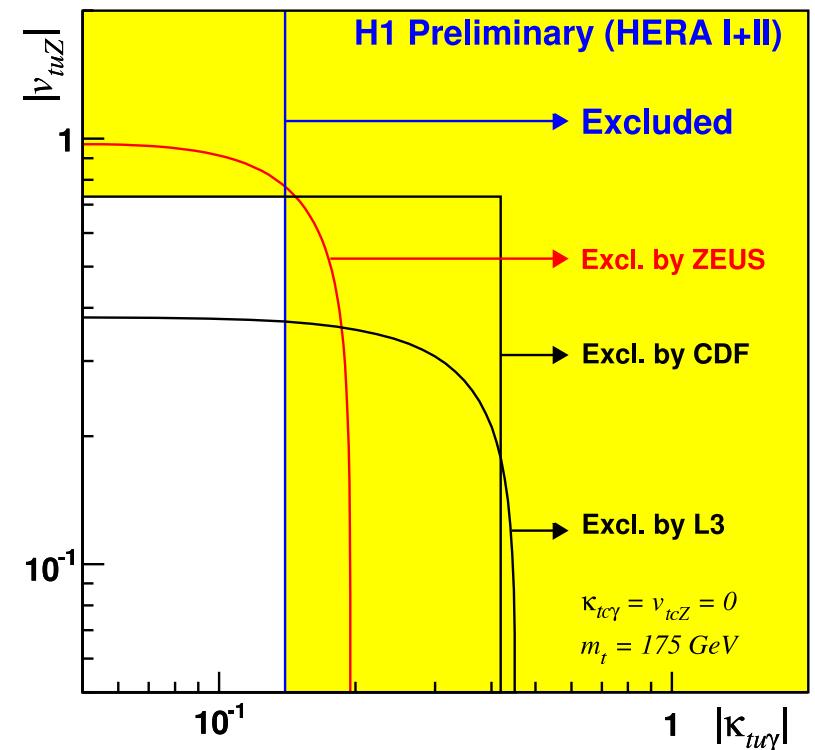
Single top could also be produced at HERA

- SM production (via W) too small
- Anomalous production from γ, Z
- Flavour changing neutral currents

H1 & Zeus find no deviation from the SM:

Limits for anomalous couplings to γ und Z .

H1: Full HERA dataset analysed



Decays

Flavour changing neutral currents

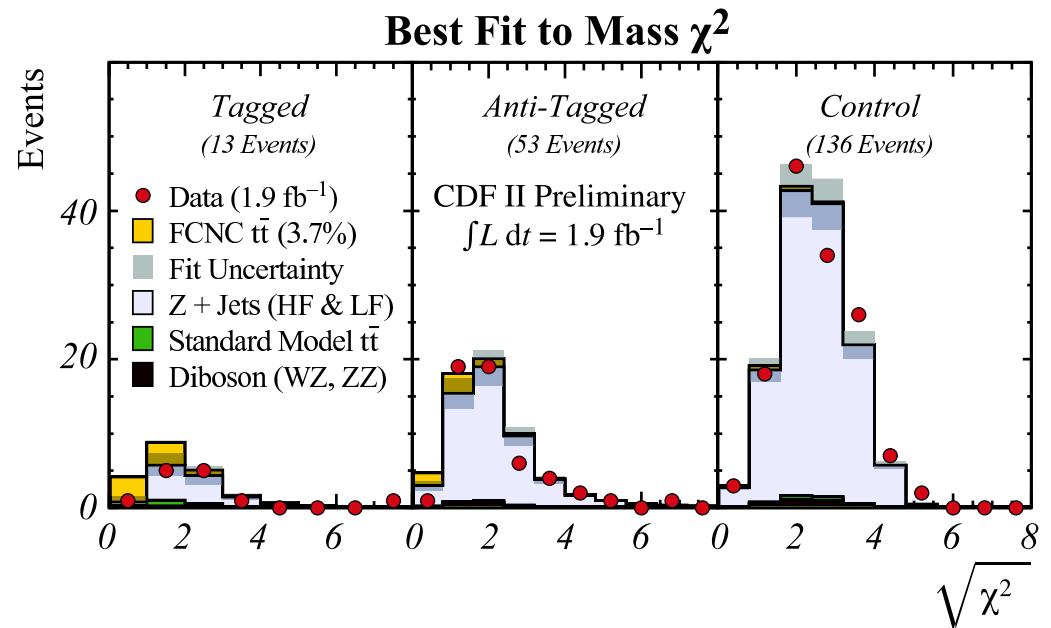
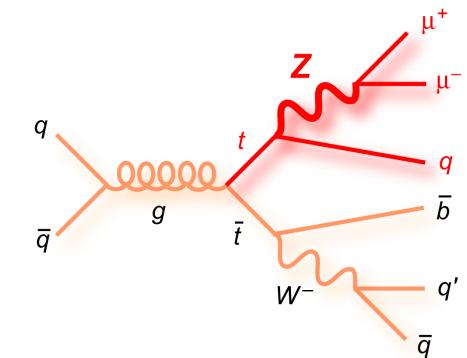
Selection: e^+e^- und $\mu^+\mu^- + 4\text{jets}$ $M_{\ell\ell} \approx M_Z$

Build χ^2 from mass constraints
(Reconstructed top and W masses)

Fit of signal and SM simulation
to χ^2 -distribution from data

$$B(t \rightarrow Zq) < 3.7\% \text{ (95\% C.L.)}$$

$$L = 1.9 \text{ fb}^{-1}$$



Many other top quark results

- Search for charged Higgs in top decay
- W -Helicity in top decay
- Production of stop squarks
- Measurement of the electrical charge of the top quark
- Search for W'
- Top quark width
- Top quark lifetime
- Contribution of production through quarks and gluons.
- . . .

Summary

- Top physics is a interesting window to new physics
 - Tevatron is still the only place to do top physics
 - LHC will take over soon
- Mass measurements are limited by theoretical issue
 - New world avarage: $m_t = 172.6 \pm 0.8(\text{stat}) \pm 1.1(\text{syst}) \text{ GeV}$
 - But what mass is this?
- Verification of
 - Production properties
 - Decay modes and decay propertiesso far show no sign of deviation from SM

